The 2010 Chile Earthquake: a five-year reflection

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ABSTRACT: At 3:34AM local time, on February 27th, 2010, a moment magnitude M_w 8.8 megathrust earthquake struck offshore the coast of Chile. The earthquake ruptured a 540 by 200 km mature seismic gap of the underlying subduction pacific plate interlocking mechanism. More than 75% of the 16 million Chileans spread over several large urban areas in the center-south of the country were affected by the earthquake, which caused 521 fatalities with 124 of them due to the tsunami, and an overall damage estimate of USD 30 billion. Because the earthquake struck the most densely populated area of the country, it represents a very unique opportunity to reflect on its ubiquitous impact over many different physical and social systems. The reflection contained in this article occurs five years later, once reconstruction and recovery are complete from this *longitudinal wound* of the country. Seismic codes have changed, research on the supposedly indestructible reinforced concrete shear walls has been done, new seismic protection technologies have been incorporated, and whole new seismic standards have been adopted by communities and people. The price it took was quite high, but we can confidently say that Chile is better prepared today for the next large earthquake.

1 INTRODUCTION

One after the other, earthquakes are still the main source of empirical information to improve our current engineering practices and to identify the new future challenges of this discipline. The progress in earthquake engineering in the last 50 years is quite remarkable, but there are still many challenges that have not been satisfactorily addressed in a scientific manner. Consequently, the motivation for this article is to provide a reflection at different time frames on the most important successes, mistakes, and lessons derived from the large megathrust earthquake of 2010 in central-south Chile that could also inform seismic engineering in the rest of the world. This reflection comes from field observations and specific research done on topics during the emergency, early response, recovery, and mitigation phases.

Because the complexity of any urban development increases continuously in time, even if we reasonably assume that for the operational lifetime of our built environment the earthquake hazard remain essentially invariant in time, the complexity of dealing with future disasters in our mega cities is only meant to increase. Such inherent increase in complexity may have serious consequences that affect our sustainable development if not addressed properly. Moreover, this increase in complexity does not only come from the increasingly interdependent built environment, but also from the increasing complexity of human expectations and interactions with such environments and among individuals.

This article builds on some scientific results and incorporates some reflections distilled from these results that could also serve other earthquake-prone societies to anticipate certain behaviours and improve their current earthquake resilience. The article starts with an overview of the 2010 earthquake problem and the overall performance observed on the built environment. It then continues with the analysis of one of the main results of this earthquake, the unexpected behaviour of reinforced-concrete shear wall buildings, to end with some reflections on different topics highlighted by this earthquake.

2 THE EARTHQUAKE

The megathrust earthquake struck central Chile at latitudes 33 through 38 at 6:34:14 UTC, and mobilized a section of 540 km by 200 km of the underlying Nazca plate. The event released a seismic moment of $1.8 \cdot 10^{22}$ N · m, and the rupture propagated bilaterally north and south from the focus; the hypocenter was located at 35.91°S – 72.73°W and 35 km deep. In this region, the Nazca plate and South American continental plate converge at a rate of about 68 mm/year. Previous studies (e.g. Delouis et al. 2010; Lin et al. 2013; Tong et al. 2010; Vigny et al. 2011) have obtained models of co-seismic slip distributions for the 2010 Maule earthquake using InSAR and GPS data. Shown in Figure 1 is the interferogram done after the earthquake (Fortuño et al. 2014), which shows the extension of the fault, as well as the distribution of slip obtained through inversion of ascending interferometric images. Slip models differ among authors, but all show that the slip direction is predominantly updip with a downdip rupture limit that ends at the intersection of the subduction plate with the continental Moho (Tong et al. 2010). The maximum slip was located north of the epicenter near the town of Pichilemu (161 km southwest of Santiago), reaching values in the range 15-20 m (e.g. Delouis et al. 2010; Lin et al. 2013; Tong et al. 2010; Vigny et al. 2011). A secondary patch of large slip was found south of the epicenter near Lebu (536 km southwest from Santiago). Based on InSAR results, it is possible to identify two zones of major co-seismic displacement gradient, the Arauco Peninsula (37.15°→37.4°S, 73.42°→73.67°W) and Pichilemu (34.4°S, 72.0°W), south and north from the epicentre (Tong et al. 2010), respectively. Maximum vertical displacements occurred at the southern cluster with values up to 1.7 m (Lin et al. 2013; Vigny et al. 2011), which are consistent with field observations. Larger horizontal displacements were measured along the coast from Constitucion (35.33°S, 72.42°W) to the south (Lin et al. 2013; Vigny et al. 2011) with values ranging between 3.3 to 5 m (Delouis et al. 2010; Vigny et al. 2011).

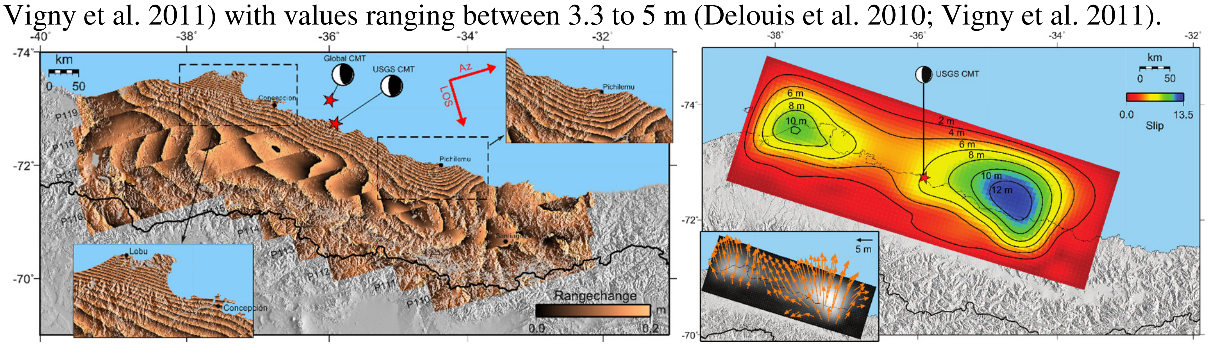


Figure 1. Interferometric analysis and slip distribution of the 2010, Chile earthquake

The sea floor deformation caused by the earthquake generated a tsunami that affected over 500 km of coast. The tsunami reached a run up height of 29 m in Constitucion and caused 124 victims (69 in Maule, 33 in Biobio, 18 in Robinson Crusoe Island and Easter Island, and 4 in Mocha Island) of the total of 521 earthquake fatalities. Because the memory of the great 1960 Valdivia earthquake is still alive, local people evacuated immediately to higher land, and most of the victims of the tsunami were tourists who stayed on low-land campgrounds.

The minutes after the 27-F event were very confusing, and the lack of information caused a very serious public and later political affair, especially since the tsunami alarm raised by the Pacific Tsunami Warning Center five minutes passed the earthquake was neglected by local authorities. Therefore, an official evacuation plan and tsunami warning was not in place prior to the arrival of the first large waves, fifteen and twenty minutes after the earthquake. The entire incident led to formal legal actions. In March 2014, four years after the earthquake, the manager of the National Emergency Office (ONEMI) in charge of the operation of the Early Warning Center the night of the earthquake was convicted as responsible of the tsunami deaths. The investigation on the failed tsunami alert was closed on July 2014, but the accusation and trial for the tsunami deaths of the former undersecretary of Interior, former ONEMI director, former Early Warning Center head, former SHOA (Hydrological and Oceanographic Service of the Navy) director, and two former SHOA officials, is still ongoing. An interesting summary of the sequence of events is summarized elsewhere (de la Llera et al. 2015).

3 PERFORMANCE OF HOUSING AND INFRASTRUCTURE

The large N-S extent of the earthquake and the rapid economic development of the country in the last 25 years exposed an important part of Chile's assets and population to the strong and long duration shaking of this earthquake. For instance, the number of households affected by the earthquake exceeds 4 million; of these, just 23.8% were insured, and about one-fifth was damaged and had insurance claims.

Moreover, the insured losses were estimated at $8 billion USD, of which just 11 million were retained by local insurance companies. The government estimated the direct and indirect losses due to the earthquake and tsunami in $30 billion USD—about 18% of Chile's GDP—being the industrial, fishing, tourism, housing, and education sectors the most affected. About 71% of these losses correspond to the aggregation of property destruction, future GDP losses, and emergency expenses that reached $1.7 billion USD. According to OECD, of the G-20 plus some other selected countries, Chile represents the largest percentage of the GDP in damage attributed to catastrophes in the last 32 years (1.36%), which is equivalent to more than $2.5 billion USD per year.

Lifelines and critical infrastructure were severely affected by the earthquake. Of the 130 public hospitals in the regions affected by the earthquake, the Ministry of Health reported that four hospitals were condemned, twelve had loss of function greater than 75%, eight operated only partially after the main shock, and 62% needed repairs or replacement. Of the beds in public hospitals, 18% continued to be out of service one month after the earthquake. Given this widespread damage of healthcare delivery facilities, a multi-section interview questionnaire was drafted and designed to capture qualitative and quantitative information on the effects of the earthquake on hospital operations and facility responses to those effects. A study area in the Biobio Region was chosen to assess the impact on a regional hospital system. The study area included seven public hospitals, seventeen health centers, and no private hospitals. The damage observed to structural, non-structural, and mechanical, electrical, and plumbing systems by the reconnaissance team in the hospitals of the study are described in detail elsewhere (e.g. Mitrani-Reiser et al. 2012). All hospitals suffered some physical damage, though all but one saw reductions in multiple services for up to a week. More than a quarter of the hospitals reported impact to their operating rooms, outpatient clinics, kitchen, laundry, and their administration due to earthquake damage. In terms of clinical services, the main regional hospital suffered more than a 50% reduction in bed count. The most frequent interruption of non-clinical services was due to the loss of patient medical record organization. The records were not backed up electronically, and took from a day to a week to restore the paper files. Food preparation and laundry services were a problem in two of the seven hospitals. In summary, although none of the surveyed hospitals suffered catastrophic collapse or any directly-related fatalities, there was sufficient damage to significantly impair patient care. This contrasts with the extremely successful earthquake performance of 4 healthcare facilities that were seismically isolated in Santiago (3) and Viña del Mar (1).

Also, one third of the schools were also seriously affected by the earthquake and tsunami, leaving 1.25 million children without classes at the start of the school year. The Ministry of Education (MINEDUC) inspected four thousand schools in the five affected regions, and reported 24% of them undamaged, 45% with minor damage, 27% with moderate damage, 3% with severe damage, and 1% with total structural damage needing immediate replacement. A quick damage assessment to tag the structures was performed to decide on the need of an emergency structural stabilization. Undamaged schools and schools with minor damage were allowed to start classes normally, while those with moderate and severe damage were partially open after the relocation of students in other public schools. MINEDUC focused on avoiding missing the school year, and managed to bring all affected children back to classes within 45 days after the earthquake. A year later, a detailed damage assessment (structural and non-structural) and the structural retrofit project of the 51 schools with total damage were carried out.

Several port structures south of the epicentre were severely damaged. Field research of the damage observed in 14 of these ports was conducted in two phases and is reported in Brunet et al. (2012). The first phase aimed to gather field data soon after the earthquake. It included technical visits to the ports to find out which structures suffered significant structural damage, and to classify the type of damage. In most cases, visitors were not allowed to get detailed observations of port damage and failed structural elements were not easily accessible. The second research phase began approximately a year later, and involved recollection of structural design information, geotechnical data, research on common failure mechanisms and patterns, and analysis of all structural sources of failure. Several obstacles were faced during this second research phase, especially concerning the quality of the available design information. Despite the help of institutions and people, the information collected was less than optimal for research purposes; structural drawings in some ports were not updated to as-built conditions and had rather poor non-digital formats. Moreover, it was also very difficult to determine repair costs due to confidentiality of the insurance claims. One counterexample of excellent earthquake performance was the seismically isolated Coronel port, which was the only port in the region that remained operative after the earthquake.

The Ministry of Public Works (MOP) reported that the earthquake and tsunami damaged public infrastructure over a large portion of the most populated Chilean territory in 1701 locations, of which 748 were associated with potable rural water networks, 717 with the road network, 54 with the river defenses, and 21 with the rainwater collectors. The assessment of public infrastructure was performed by MOP during the emergency response and the reconstruction. The emergency response focused on recovering connectivity in the country through the road network. The National Roads Department sent engineers to each of the four most affected regions for a week of quick evaluations; the inspections were conducted without a predefined protocol and without carrying structural drawings of bridges. Each group had the authority to close a road and decide to install special road signals or a flagman, limit traffic weights, or install temporary bridge supports. For the long-term reconstruction, MOP performed a detailed inspection of damaged infrastructure, and generated a global geographical database, mounted on their intranet system, to facilitate monitoring of the reconstruction projects.

One of the first consequences of the earthquake was the loss of electric power in a vast area of central Chile, which caused the communication media (radio and television) to go down (de la Llera et al. 2015). Radio stations (AM/FM) recovered faster, relying on their diesel electric generators just a couple of minutes after the earthquake. The cellular network collapsed shortly after the earthquake and the landline phone network experienced severe congestion. Immediately after the earthquake, the number of cellular call attempts increased dramatically, reaching 24 times the value expected in a normal day and three times the value of New Year's Eve. This demand clearly outran the capacity of the network. As the electric power went down for several hours in some places, this affected the operation of some vital parts of the cellular network: base transceiver stations (BTS), base station controllers, and mobile switching centers. Of all the BTS that went down during the earthquake, 2% were damaged by the earthquake itself, and 34% went down within 20 minutes of the electric power failure, mainly due to failure of the power backup systems. The rest (64%) were operational between 2 and 8 hours before failing.

The emergency communications systems failed due to: (i) the emergency communication network's strong dependence on public services (fixed and cellular telephone networks), which broke down by lack of power and/or congestion; (ii) lack of maintenance of the HF and VHF emergency networks with operation protocols that were outdated; (iii) discharged batteries of a number of available satellite telephones; and (iv) outdated information at the emergency center. Moreover, the earthquake affected the area covered by the Central Interconnected System (SIC), which provides electricity to over 90% of the Chilean population. The earthquake produced a blackout of 4522 MW out of 6145 MW at peak demand. A 693 MW power plant was affected and had to shut down for major repairs. The grid was able to operate and power was restored within a few hours, but severe damage occurred in the distribution network, where repairs took several days to weeks to complete.

4 PERFORMANCE OF SHEAR WALL BUILDINGS

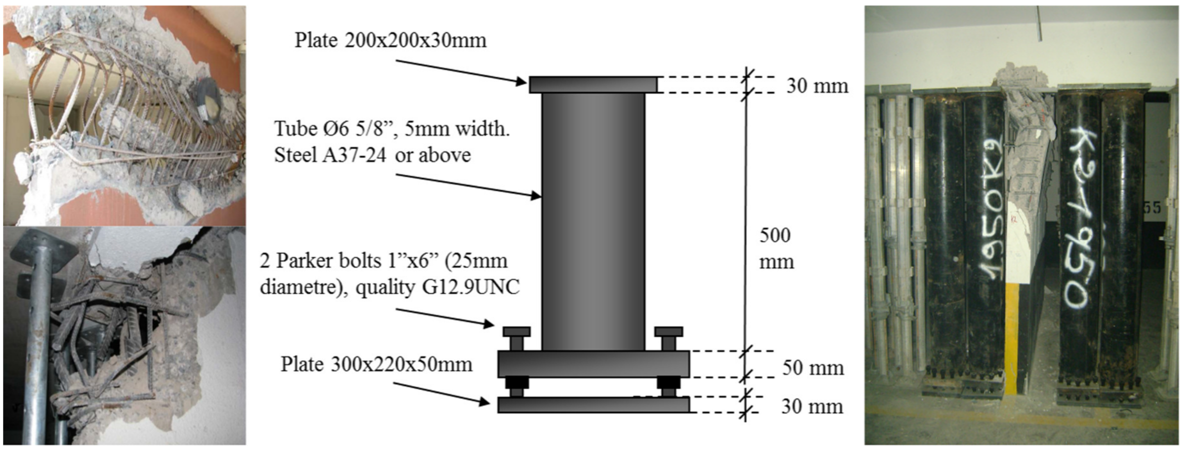
The seismic performance observed in several shear-wall buildings was somewhat surprising, especially if compared with the performance of shear-wall buildings after the March 3rd, 1985, central Chile earthquake. Indeed, apart from the 16-story Alto Rio building that collapsed during 27-F and killed eight people, a good number of other reinforced concrete buildings in the cities of Santiago, Viña del Mar, Curico, Talca, Chillan, Concepcion, and surroundings suffered similar patterns of brittle structural damage in shear walls, some of them leading to a rather unstable condition of the structure (Fig. 2). The estimates are that about 46 buildings were severely damaged during this earthquake, which represents about 2% of the total inventory of shear-wall buildings 9-stories and taller (Jünemann et al. 2015a).

(a) (b) (c)

Figure 2. Typical brittle failure in RC walls during the 2010, Maule earthquake: (a) building in Santiago; (b) building in Concepción; and (c) building in Viña del Mar.

Chile is a country of frequent large earthquakes, and when they strike, a large majority of the structural engineers become involved still as active professionals and building designers. Indeed, right after the earthquake, structural engineering firms checked the condition of their previously designed buildings using internal protocols. This informal self-inspecting practice of companies is very unique, and generates relevant information on the status of buildings. When building damage was discovered, at least two detailed independent studies were usually requested by constructors, owners and/or the respective municipal administration. These studies included inspections of the damaged components of the primary and secondary structural system, and included suggestions for retrofit.

If any building was severely damaged and at risk of collapse with the aftershocks, it was necessary to propose in a few days an emergency stabilization procedure, even before people could enter to inspect or do any work inside these structures. This was the case of several tall buildings, whose stabilization process provided very unique and useful information to other projects that followed a similar stabilization methodology (de la Llera et al. 2015). The emergency stabilization strategy was to install an important number of vertical struts readily available in the market; however, since these elements have low axial capacity, a more reliable solution was required due to high-intensity aftershocks. This solution consisted of 10” Yoder pipes with Parker bolts installed directly below the wall offset and continuously at all basement levels (see Fig. 3b and c). The bolts were used to preload the pipe and carry vertical load. These high strength pipes had Parker bolts that were calibrated to control the load on each element and avoid damage in slabs. This procedure was used in a large number of severely damaged buildings and was very successful.



(a) (b) (c)

Figure 3. Damage and shoring system: (a) boundary damage and temporary shoring; (b) Yoder pipes and stabilization solution typically used for buildings; and (c) implementation of the stabilization solution at the basement level of a building in Santiago

As soon as the emergency was over, several analytical and experimental studies started with the aim of better understanding the earthquake behaviour of these shear wall buildings that underwent considerable damage during the earthquake, with some of them critically damaged. The brittle failure of shear walls observed during the earthquake was also reproduced in the laboratory under similar loading conditions

(Alarcón et al. 2014). Yet, the question remains on how and why some of these resisting planes failed and others did not. With that goal in mind, a tripartite methodological strategy was developed to delimit the solution to this problem. First, a comprehensive statistical and parametric analysis was performed to identify certain anomalies in these buildings by using damage data and correlating it with global dynamic parameter data (Jünemann et al. 2015a). It turns out that it is difficult to get general conclusions exclusively based on global building dynamic parameters, and a more refined analysis is necessary. Such analyses have been performed at the section, resisting plane, and 3D building level. At the section level, it is possible to show that these walls are inherently brittle given their high axial stresses and their lack of boundary confinement (Fig. 3a), but certainly not sufficiently different from that of other shear wall sections that did not fail (Jünemann et al. 2015b).

Thus, a pushover analysis was used to reproduce the observed damage in a few resting planes. These analyses considered different lateral loading configurations, and their goal was to reproduce the mechanism of collapse of selected resisting planes. This turned out to be an interesting problem and the results identify a specific loading pattern that generates the almost exact failure geometry. A key aspect to this pattern is to include the vertical deformations at the edges of the resisting plane. As it is shown in Figure 4, if such deformations are omitted, the geometry of the failure changes substantially. This failure of the resisting planes occurs, without any adjustment of parameters, in the exact location where it occurred during the earthquake. However, it is apparent that the different stress-strain relationships considered do have an influence on the rupture mechanism (Jünemann et al. 2015b).

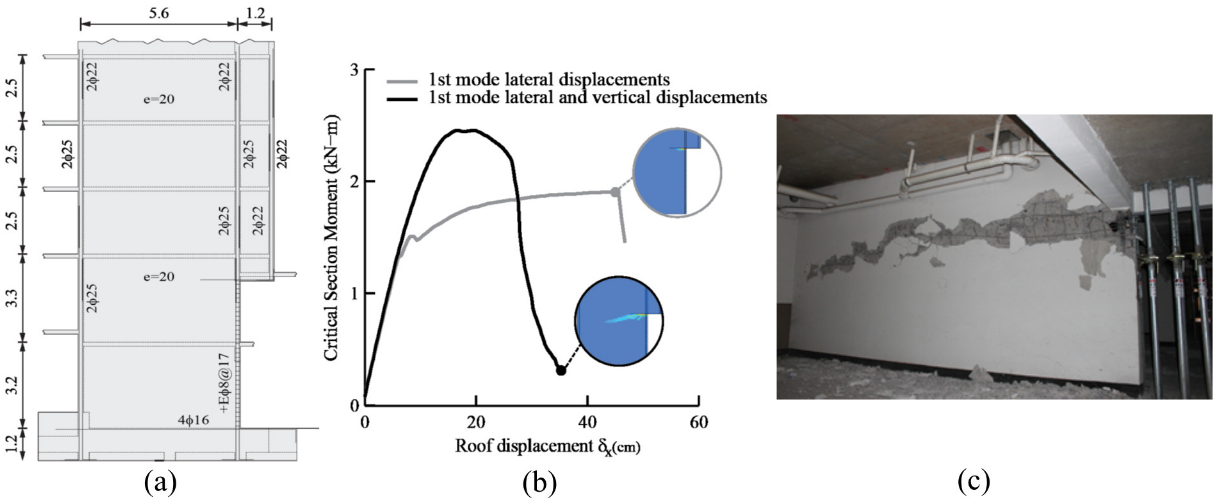


Figure 4. Building analysed: (a) elevation of a resisting plane of building in Santiago (dimensions in meters); (b) pushover results for the moment-displacement curve with (black line) and without (grey line) vertical deformations; and (c) observed damage pattern reproduced analytically.

The next big challenge was to validate through non-linear dynamic analysis if the successful load pattern considered for the pushover analysis was real. For that purpose, an inelastic analysis of the building was performed using a new flexibility based inelastic element with distributed plasticity, which has been recently developed (Vásquez et al. 2015). Although the dynamic model of the building shows the collapse of the exact same resisting planes as the ones that failed, the model still needs refinement to validate the assumption of the pushover analysis. It is fair to say though that the observed failure could be predicted by using currently available inelastic dynamic analysis tools.

5 LESSONS LEARNED

The 2010, Chile earthquake brought with it a real treasure of information for seismic engineers. First, it is quite remarkable that available InSAR technology can provide such a precise representation of the co-seismic displacement field of the earthquake in very short time, which enables us, among other things, to infer a rupture model and from there provide realistic synthetic ground motions over a large area, not necessarily instrumented. It is apparent that the characterization of the earthquake hazard has improved considerably over the years, which will result in more realistic design spectra—the design spectra of the NCh 433 Chilean seismic code was rapidly changed as a result of this earthquake. The design spectra of the other local seismic code, the seismic isolation code NCh 2745, which is 0.1g at PGA larger than NCh 433, proved to be more consistent with this earthquake as shown in Figure 5.

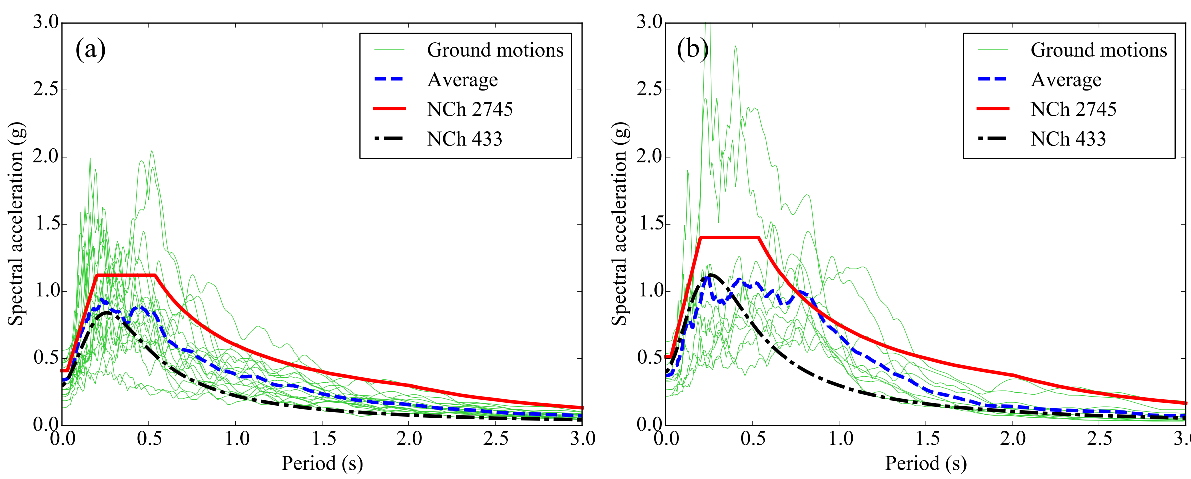


Figure 5. Design spectra from the NCh433 and NCh2745 Chilean seismic codes, and from recorded ground motion accelerograms of the 2010 Chile earthquake near to the fault plane (from 33°S to 38.5°S), in soil type II, and: (a) zone II (central valley), and (b) zone III (coast).

The biggest surprise occurred with the supposedly indestructible shear wall buildings, which showed that they may behave in a very brittle manner, which is particularly dangerous and sensitive to the level of axial stress. Although laborious, available state-of-the-art inelastic models may identify these critical walls and sections within a structure, from a design point, the earthquake behaviour of these buildings is inconsistent with the assumptions in ductility expressed through current R-factors in Chilean building codes, and other codes as well. Models prove that most transverse walls failed simultaneously, and if not for the longitudinal corridor walls, these structures could have collapsed. Limiting axial stress in RC walls in seismic environments should be mandatory for all seismic codes, in order to guarantee a minimum ductility in the walls, at least consistent with the R-factor used in design.

A lesson that is not new, but has repeated over and over many earthquakes, is the large importance of local site conditions. Structural damage is strongly correlated with poorer soil conditions, and this has also been corrected in the NCh 433 code by adding a new soil classification. Because this earthquake occurred relatively far from the metropolitan areas, high frequency waves were filtered and the earthquake mostly showed damage in medium-rise buildings and softer soils.

Another very important lesson was the extraordinary behaviour of seismically protected structures using seismic isolation and energy dissipation systems. Thirteen seismically protected structures were exposed to this earthquake, including office and institutional buildings, hospitals, houses, and ports. The 54-story Titanium tower, the tallest building in Santiago at the time, was successfully protected with C-shape metallic dampers; the largest hospital in the capital, the Military Hospital, isolated with elastomeric bearings, operated normally during and after the earthquake; and the unique isolated port in the Talcahuano and Coronel Bay that remained fully operational, are three examples. This success has produced a rapid increase in the number of structures with seismic protection in the country, reaching today more than 80. The Ministry of Health leads in innovation with a practice that pushes every hospital in Chile to be seismically isolated; this example has been followed timidly by other Ministries such as Public Works and Housing.

It is apparent from this earthquake that investing in mitigation of the devastating effects of natural disasters is wise. However, more than ever, improving earthquake resilience of a society requires a very systemic and comprehensive approach to understand the overall behaviour of the increasingly complex and interdependent functioning of growing urban and productive areas. The earthquake engineering discipline has still a lot to advance in bringing into play this systemic view that has been almost completely neglected so far, not only by improving knowledge on the disciplinary aspects of the design and response of the built environment, but also in bringing into the problem the most complex variable: the human response.

ACKNOWLEDGMENTS

This paper has been supported by research grant Fondecyt 1141187, and by the National Research Center for Integrated Natural Disaster Management (CIGIDEN), CONICYT/FONDAP/15110017. The authors are grateful also of the many colleagues, students, and collaborators which work is reflected in this publication.

REFERENCES:

Alarcón, C., Hube, M.A. & de la Llera, J.C. 2014. Effect of axial loads in the seismic behavior of reinforced concrete walls with unconfined wall boundaries. *Engineering Structures*. 73:13-23.

Brunet, S., de la Llera, J.C., Jacobsen, A., Miranda, E. & Meza, C. 2012. Performance of port facilities in southern Chile during the 27 February 2010 Maule earthquake. *Earthquake Spectra*. 28(S1):S553-S579.

de la Llera, J.C., Rivera, F., Mitrani-Reiser, J., Jünemann, R., Fortuño, C., Ríos, M., Hube, M., Santa María, H. & Cienfuegos, R. 2015. Data collection after the 2010 Maule earthquake in Chile. *Bulletin of Earthquake Engineering*. Submitted for publication.

Delouis, B., Nocquet, J.-M. & Vallée, M. 2010. Slip distribution of the February 27, 2010 Mw 8.8 Maule earthquake, central Chile, from static and high-rate GPS, InSAR, and broadband teleseismic data. *Geophysical Research Letters*. 37(17):1–7.

Fortuño, C., de la Llera, J.C., Wicks, C.W. & Abell, J. 2014. Synthetic hybrid broadband seismograms based on InSAR coseismic displacements. *Bulletin of the Seismological Society of America*. 104(6). doi: 10.1785/0120130293.

Jünemann, R., de la Llera, J.C., Hube, M.A., Cifuentes, L.A. & Kausel, E. 2015a. A statistical analysis of reinforced concrete wall buildings damaged during the 2010, Chile earthquake. *Engineering Structures*. 82:168-185.

Jünemann, R., de la Llera, J.C., Hube, M.A., Vásquez, J., Chacón, M. 2015b. Study of the collapse of reinforced concrete shear walls during recent earthquakes. *Earthquake Engineering and Structural Dynamics*. Submitted for publication.

Lin, Y.N., Sladen, A., Ortega-Culaciati, F., Simons, M., Avouac, J.-P., Fielding, E.J., Brooks, B.A., Bevis, M., Genrich, J., Rietbrock, A., Vigny, C., Smalley, R. & Socquet, A. 2013. Coseismic and postseismic slip associated with the 2010 Maule Earthquake, Chile: Characterizing the Arauco Peninsula barrier effect. *Journal of Geophysical Research: Solid Earth*. 118(6):3142–3159.

Mitrani-Reiser, J., Mahoney, M., Holmes, W.T., de la Llera, J.C., Bissell, R. & Kirsch, T. 2012. A functional loss assessment of a hospital system in the Bío-Bío Province. *Earthquake Spectra*. 28(S1):S473-S502.

Vásquez, J., de la Llera, J.C. & Hube, M.A. 2015. A regularized fiber element model for reinforced concrete shear walls. *Earthquake Engineering and Structural Dynamics*. Submitted for publication.

Tong, X., Sandwell, D., Luttrell, K., Brooks, B., Bevis, M., Shimada, M., Foster, J., Smalley Jr., R., Parra, H., Báez Soto, J.C., et al. 2010. The 2010 Maule, Chile earthquake: Downdip rupture limit revealed by space geodesy. *Geophysical Research Letters*. 37(24):1–5.

Vigny, C., Socquet, A., Peyrat, S., Ruegg, J.C., Métois, M., Madariaga, R., Morvan, S., Lancieri, M., Lacassin, R., Campos, J., et al. 2011. The 2010 Mw 8.8 Maule megathrust earthquake of Central Chile, monitored by GPS. *Science*. 332:1417–1421.